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The synergy between drought and extremely hot summers in the Mediterranean

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LETTER

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Abstract

In the last years a large number of weather driven extreme events has occurred worldwide with unprecedented socio-economic impacts and are expected to increase, in both frequency and intensity, under future global-warming conditions. In this context early identification and predictability of such events are paramount as they mostly affect several socio-economic activities. Despite the effort in monitoring and evaluation of these extreme events, a quantitative assessment of their interaction is still a challenge. We propose to analyze if the occurrence of extremely hot days/nights in the summer is preceded by drought events in spring and early summer throughout the Mediterranean area. This was investigated by correlating the number of hot days and nights in the regions hottest months with a drought indicator on the prior months. Drought characterization was performed using both the Standardized Precipitation Evaporation Index (SPEI) and the Standardized Precipitation Index (SPI) for the 3-, 6- and 9-months time scales, considering the period 1980–2014 with a spatial resolution of 0.5°. The number of hot days and nights per month (NHD and NHN, respectively) is determined for the same period and spatial resolution. Results show that the most frequent hottest months for the Mediterranean region occur in July and August. Most regions exhibit statistically significant negative correlations, i.e. high (low) NHD/NHN following negative (positive) SPEI/SPI values, and thus a potential for NHD/NHN early warning. This analysis allowed to identify the Iberian Peninsula, northern Italy, northern Africa and the Balkans as the main hotspots of predictability of extreme hot temperatures in the summer preceded by the occurrence of drought events in the spring or early summer.

1. Introduction

Record-breaking Extreme Natural Events (ENE) have been occurring frequently worldwide (IPCC 2012) and are further expected to increase in both frequency and intensity under future global-warming conditions (Sillmann *et al* 2013, Spinoni *et al* 2017). Europe has experienced multiple ENE, namely, severe droughts (Trigo *et al* 2013) and mega-heatwaves (García-Herrera *et al* 2010, Bastos *et al* 2014, Sánchez-Benítez *et al* 2018). These ENE had a wide range of negative impacts on agriculture (Bastos *et al* 2014, Páscoa *et al* 2017), vegetation activity (Gouveia *et al* 2016), forest fires (Turco *et al* 2017) and in health (Díaz *et al* 2006, Trigo *et al* 2009).

Despite the intense emphasis devoted to ENE from international authorities and governments, as well as from numerous scientists worldwide, the quantitative assessment of drought and heatwave events continues to be very challenging, particularly due to the existence of several definitions of drought (Lloyd-Hughes 2014) and the use of different criteria to characterize ENE. On the other hand, added difficulties to the modeling of future extreme events in the context of climate change will occur, mainly due to the projected new kind of events that we may face in the future (IPCC 2012). It is now clear that the frequency of drought events in the Mediterranean basin has increased significantly in the last decades (Vicente-Serrano *et al* 2014), which is in accordance with the

expected tendency towards more frequent dry periods in a future warmer climate (IPCC 2012, Soares *et al* 2017).

The assessment and monitoring capabilities of droughts and heatwaves have improved significantly in recent years, mainly due to growing computational modeling capacity and new data acquisition methods (e.g. satellite-based data). The success of the anticipation of drought consequences and their mitigation is largely dependent on a continuous monitoring of soil moisture (SM), which is usually difficult (Seneviratne *et al* 2010). In practice many studies rely on SM proxies to study the relationship between SM deficits and other variables. The contribution of newly focused approaches which rely on extreme indices (IPCC 2012, Sillmann *et al* 2013), multi-scalar drought indices (e.g. Standardized Precipitation Index (SPI, McKee *et al* 1993), Standardized Precipitation Evapotranspiration Index (SPEI, Vicente-Serrano *et al* 2010) and Extreme Value Theory (IPCC 2012), can pose as essential to analyze these extreme events and their impacts. Specifically, SPI and SPEI are surrogate measures of SM (Herold *et al* 2016), allowing for an indirect assessment of SM and compensating for the sparsity of the available historical records (Robock *et al* 2000). Both these indices have the particularity of being multi-scalar allowing for the analysis of droughts at distinct time scales. This is important as different systems and regions respond to drought at very diverse temporal scales (Vicente-Serrano *et al* 2010).

Indices for extreme temperature events are widely used, often by assessing days with temperatures above or below specific physically-based thresholds (Zhang *et al* 2011, Russo *et al* 2014). Threshold-based indices do not allow for a direct comparison for different study areas or time periods and are out passed by percentile thresholds, as they are more evenly distributed in space and are comparable between different regions. These methods are particularly suited to analyze global warming consequences on ENE and they are tailored to account for unusual or frequently unusual ENE (IPCC 2012). A growing number of works have also focused on the characterization and quantification of the positive feedback between droughts and extreme hot days, as it has been considered as a relevant factor for past heatwaves and temperature extremes (e.g. Hirschi *et al* 2011, Mueller and Seneviratne 2012, Miralles *et al* 2014, Schubert *et al* 2014, Sharma and Mujumdar 2017). Drought conditions may lead to an increase of ENE through a SM feedback, such as a decrease in evapotranspiration and an increase in sensible heat flux (Mueller and Seneviratne 2012). Thus, it is vital to further investigate to what extent are these ENE related and how they could be predicted to mitigate the consequences (identification of triggering and constraining mechanisms), allowing for the development of tools for early

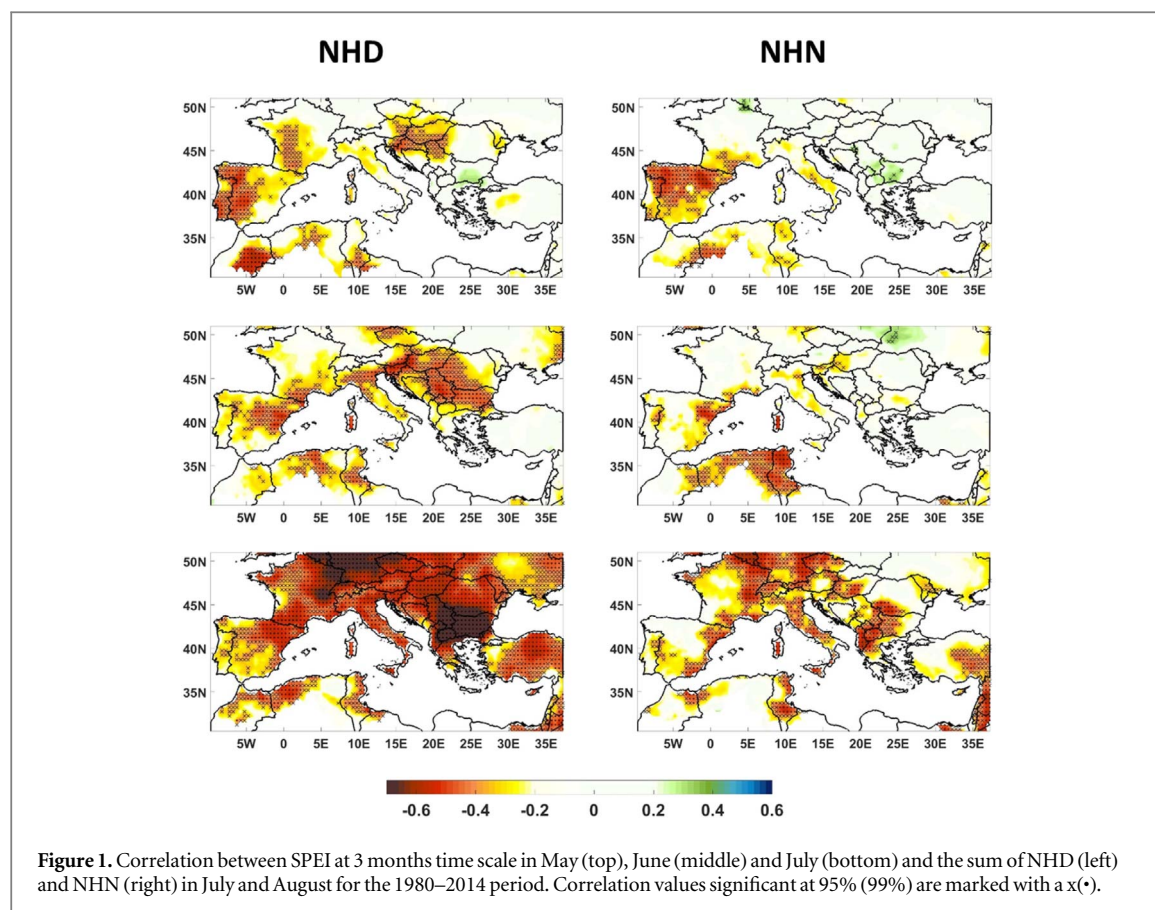
warning actions (Hirschi *et al* 2011, Quesada *et al* 2012, Mueller and Seneviratne 2012).

This work is focused on the potential of using SM deficits to derive predictive information on the occurrence of ENE through direct and multi-scalar approaches. The proposed multi-scalar drought index method builds from several studies (e.g. Quesada *et al* 2012, Miralles *et al* 2014, Schubert *et al* 2014) and will be used as proxy for SM deficits, which will allow to assess the impact of the SM deficits on the occurrence of subsequent extremely hot temperature events. Our analysis aims (i) to characterize the evolution of drought in the Mediterranean by means of two multi-scalar drought indices, SPI and SPEI; (ii) to identify the occurrence of temperature extremes by means of percentile-based indices; (iii) to analyze to what extent the occurrence of extreme hot months in Mediterranean region is preceded by the occurrence of droughts, both though the use of SM estimated values, as well as, by the two multi-scalar drought indicators. To achieve this goal, we evaluated the link between the number of hot days and nights in the hottest month of each year and a monthly series associated with the occurrence of droughts for the 1980–2014 period. Apart from analyzing the Mediterranean as a whole, this study will focus mainly on two distinct European regions, namely the Iberian Peninsula (IP, 36.5–44.5°N; 8.5°W–3.5°E) and the Balkan region (BKS, 40–50°N; 15–25°E). The Iberian Peninsula and the Balkans have often been identified as areas where intense land-atmosphere coupling processes with strong SM persistence occur (Mueller and Seneviratne 2012, Ardilouze *et al* 2017). The following section describes the data and methods, followed by the results and discussion with the main conclusions presented in the last section.

2. Data and methods

2.1. Meteorological drought

Meteorological drought for the 1980–2014 period was quantified using two well established multi-scalar drought indicators, SPI and SPEI, which have a long and proven record for drought characterization (e.g. Mueller and Seneviratne 2012, Beguería *et al* 2014, Herold *et al* 2016, Spinoni *et al* 2017). These indices hold a temporal multi-scalar character and their computation allows for the objective identification of the beginning and end of drought episodes as well as the quantification of their magnitude and spatial extent (Vicente-Serrano *et al* 2010, 2014). The SPI measures drought based on a probabilistic approach to precipitation (McKee *et al* 1993), whereas SPEI also account for evaporative demand (Vicente-Serrano *et al* 2010). SPEI holds the advantage of being sensitive to the temperature effect in evapotranspiration and, therefore, suitable to incorporate the global warming influence (Vicente-Serrano *et al* 2010). This advantage



solves the main criticism to SPI which does not take into account other relevant variables (e.g. temperature, evapotranspiration, solar radiation or wind speed) when a drought event is developing (Vicente-Serrano *et al* 2010). However, the temperature warming effect in SPEI can result in an exaggerated drying relative to other indicators (Cook *et al* 2014). SPEI does not account for the SM budget (as the PDSI or other indexes based on a water balance SM), that would restrict evapotranspiration below the potential evapotranspiration used in SPEI. Thus, SPEI should be used with parsimony.

The climatic data used in this study was retrieved from the Climatic Research Unit (CRU) TS (time-series) 4.01 (Harris *et al* 2014), covering the period from January 1980 to December 2014 on a monthly basis. The CRU TS 4.01 dataset covers uniformly the globe and includes monthly values of several climate variables (e.g. precipitation, temperature, Penman-Monteith evapotranspiration (PET), cloud cover and vapor pressure, among others) computed on a resolution grid of $0.5^\circ \times 0.5^\circ$.

SPI and SPEI for the 3-, 6- and 9-months' time scales were computed for the baseline period 1980–2014 for the Mediterranean (figure 1). Different time scales are associated to the fact that each one reflects the accumulated drought conditions of longer or shorter periods. The 12 month time scale is usually able to identify long-term events, being more representative of the impacts of drought on the hydrologic

regimes (Vicente-Serrano *et al* 2010). Shorter to medium time scales are useful to detect agricultural/meteorological droughts and are mainly related to soil water content and river discharge in headwater areas, and also to reservoir storages and discharge in the medium course of the rivers (Vicente-Serrano *et al* 2010, Spinoni *et al* 2017). The choice of the baseline period relatively to which the standardized drought indicators are calculated is a key factor as that may introduce some influence on the indicators trend over the entire period (Spinoni *et al* 2017). To account to the use of the last decades which show an intensification of drought events relatively to the beginning of the century (Spinoni *et al* 2017), both SPI and SPEI will be detrended after calculation (Páscoa *et al* 2017). The trend removal was applied to remove long-term signals (mainly from climate change) from the correlations as we are mainly interested in inter-annual variability. For the SPI computation, the Gamma distribution was used to model precipitation and for the SPEI, Penman-Monteiths PET from CRU TS 4.01 was used, as well as, the Log-logistic distribution to model the water deficit (e.g. Vicente-Serrano *et al* 2010, Beguería *et al* 2014).

Finally, and to evaluate if the results attained by the SM proxies are acceptable, SM from ERA-Interim/Land covering the period 1980–2014 were also used (Balsamo *et al* 2015). The ERA-Interim/Land SM is the result of a simulation with the ECMWF (European Centre for Medium-Range Weather Forecasts) land

surface model driven by meteorological forcing from the ERA-Interim atmospheric reanalysis and precipitation adjustments based on monthly GPCP v2.1 (Global Precipitation Climatology Project). The horizontal resolution is about 80 km and the time frequency is 3-hourly. ERA-Interim/Land SM product is suitable for climate studies involving land water resources, providing a global integrated and coherent estimate of SM (Albergel *et al* 2013). It should be noted that the SM product is a model's output which has limitations inherent to model formulation and driving data.

2.2. Temperature extremes

In order to detect changes in climate extremes, a range of bio-climatic indices have been developed which are statistically robust, cover a wide range of climates, and have a high signal-to-noise ratio. The relevance and applicability of these indices have been widely reviewed in a number of reports and articles (e.g. Zhang *et al* 2011). From a long list of relevant indices, we would like to highlight two, namely (1) the number of hot nights per month (NHN) index, which is defined as the number of days at each grid point where the daily minimum temperature meets or exceeds the long-term mean 90th percentile of daily minimum temperature; and (2) the number of hot days per month (NHD), which corresponds to the number of days with a maximum temperature exceeding the 90th percentile (Fischer *et al* 2007, Zhang *et al* 2011).

Here a gridded version (E-OBS version 14) of the European Climate Assessment & Data (Haylock *et al* 2008) for continental surface temperature (minimum and maximum), which has a grid resolution of $0.5^\circ \times 0.5^\circ$ and covers the period from 1980 to 2014, was used to compute the NHN and NHD.

2.3. Methodology

The association between surface moisture deficits during spring and early summer (as determined by proxies SPI and SPEI) and the occurrence of hot extreme temperatures in summer in the Mediterranean region were investigated. Building upon previously published studies (Hirschi *et al* 2011, Mueller and Seneviratne 2012, Herold *et al* 2016), the two drought indicators were used as proxy for surface moisture deficits. The impact of these deficits was assessed over the Mediterranean through correlation analysis between the drought indices calculated for 3-, 6- and 9-months time scales during the months of May, June and July and the NHN and NHD on the hottest months of the year (usually July and August). This means that the months preceding the hottest months of a particular year are considered, which in the case of the 3 month SPEI calculated in June implies, for instance, that April to June water balance will be correlated to the NHN or NHD time series relative to the following summer months.

Correlation analyses is suitable to study the relationship between two variables mean states, although it should be noted that statistical relationships do not necessarily imply causality (Mueller and Seneviratne 2012). Nevertheless, it can be used to assess the coupling between two variables if plausible mechanisms exist (Mueller and Seneviratne 2012). Several authors (e.g. Fischer *et al* 2007, Miralles *et al* 2014, Herold *et al* 2016) have already pointed the existence of a plausible mechanism—the recurrently reported feedback mechanism between SM and heat extremes—thus supporting the application of a correlation analysis approach. Although this method was previously applied with success, we consider that prior studies lack some aspects, namely when only using one proxy for SM (e.g. Mueller and Seneviratne 2012, Herold *et al* 2016); or using lower resolution datasets and not including SM data to complement the information reached using proxy datasets (e.g. Mueller and Seneviratne 2012). Thus, we are confident that this approach provides a potential solution to the referred issues, namely through the use of higher-resolution datasets from two proxies and SM data and focusing on the Mediterranean which has been recurrently affected by both ENE.

3. Results

Firstly, the yearly hottest month was identified for each grid point for the Mediterranean study area. Not surprisingly, the most frequent hottest month throughout the study period was either July or August (supplementary material, figure S1 available online at stacks.iop.org/ERL/14/014011/mmedia). To avoid time discontinuities, the NHD (NHN) were summed up at each grid point over the two months. So, correlations between the NHD (NHN) in the two hottest months (July and August) and the 3-, 6- and 9-month SPEI (SPI) computed in the preceding months were calculated at each location (figures 1–3). Results for SPI are shown in the Supplementary Material (figures S2–S4). The spatial patterns of the correlations between NHD or NHN with SPI or SPEI are generally similar (figures 1–3, figures S2–S4).

Several regions exhibit significantly negative correlations, i.e. high NHD (NHN) following negative SPEI or SPI values (figures 1–3, S2–S4, table 1). For any lead time of preceding drought conditions, the correlation of prior drought to heatwave is stronger for later in the summer than earlier in the summer or spring. The correlations between the NHD in July and August and the preceding 3-, 6- and 9-month SPEI in the month of May (Figures 1–3, top panel), in June (figures 1–3, middle panel) and July (figures 1–3, lower panel) present significant spatial differences, increasing its spatial representativeness from May to July. The correlation between preceding drought and the summer NHD and NHN presents almost as good at the 9

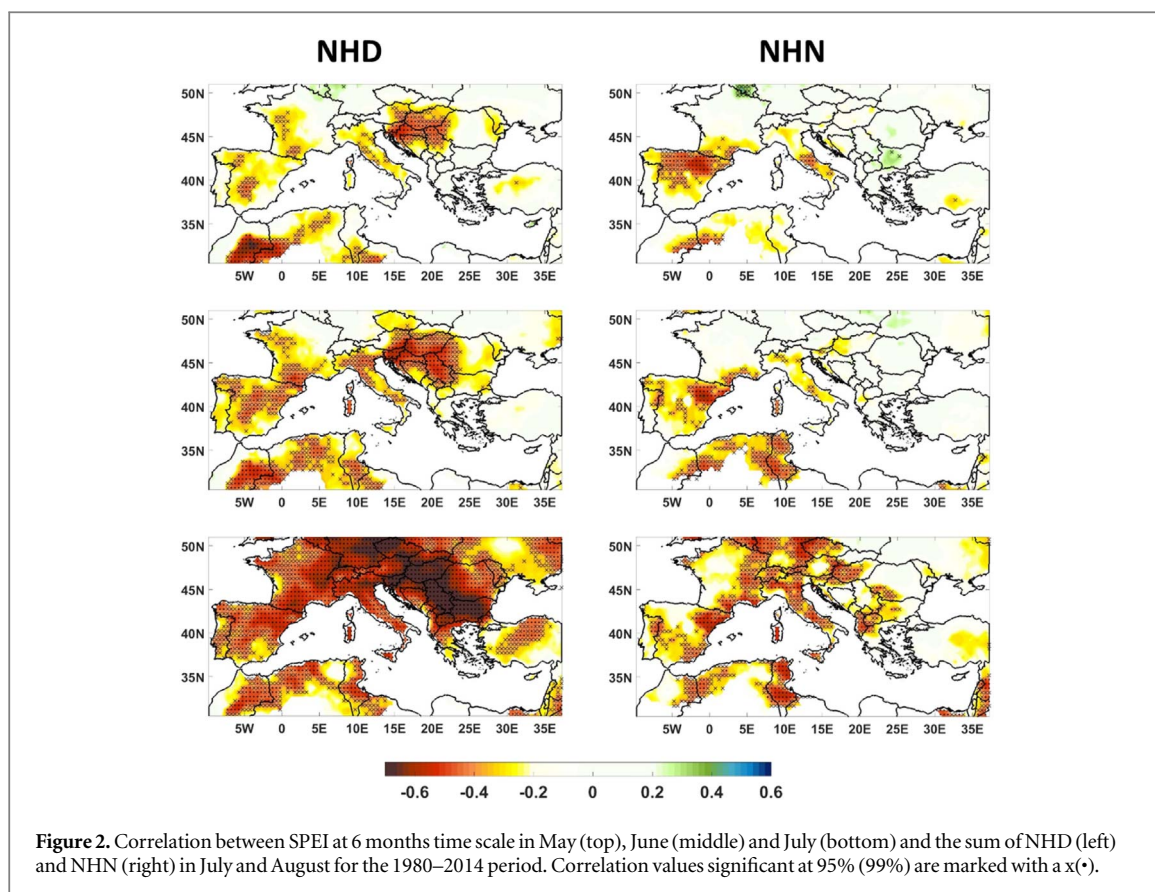


Figure 2. Correlation between SPEI at 6 months time scale in May (top), June (middle) and July (bottom) and the sum of NHD (left) and NHN (right) in July and August for the 1980–2014 period. Correlation values significant at 95% (99%) are marked with a x(•).

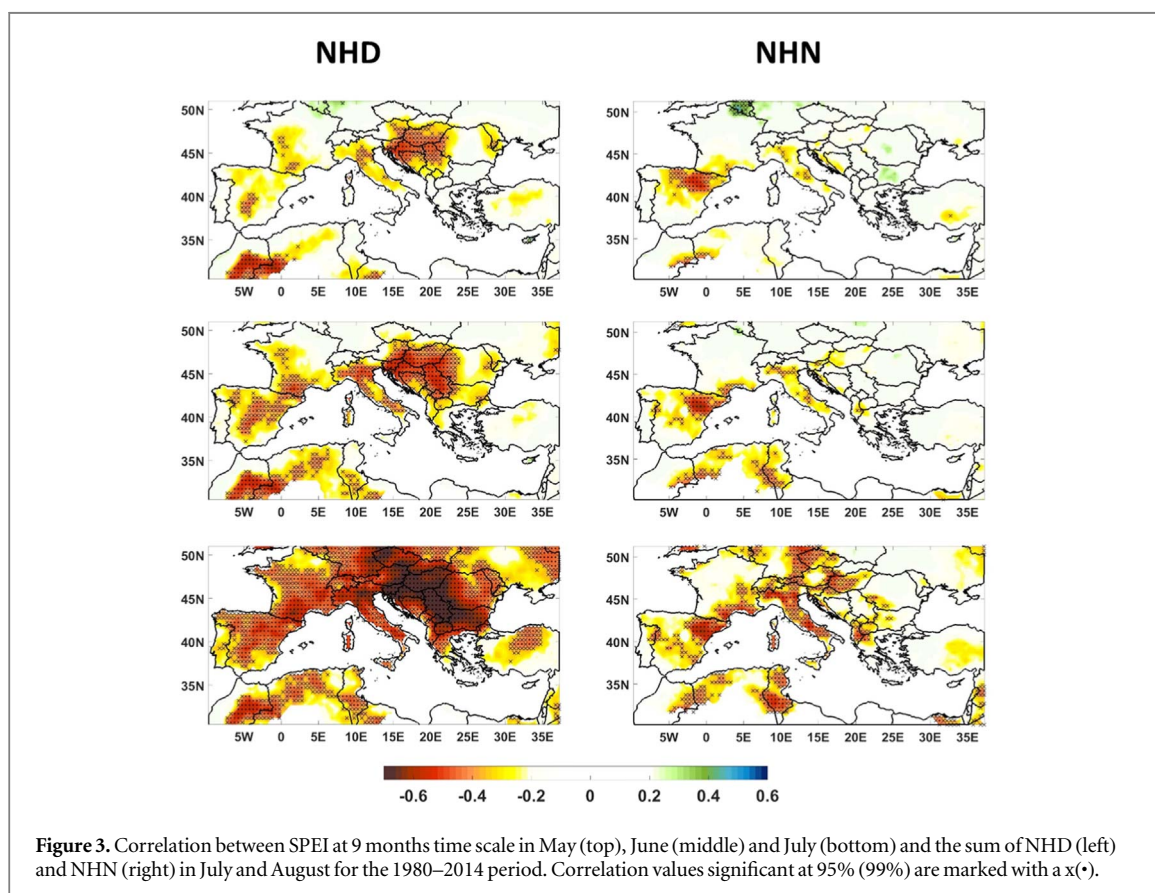


Figure 3. Correlation between SPEI at 9 months time scale in May (top), June (middle) and July (bottom) and the sum of NHD (left) and NHN (right) in July and August for the 1980–2014 period. Correlation values significant at 95% (99%) are marked with a x(•).

Table 1. Higher negative correlations for the study area (Corr) and for the Iberian Peninsula (IP) and Balkans (BKS) between SPI and SPEI at 3-, 6- and 9-months' (SPI_9 and $SPEI_9$) time scales in May, June and July and the sum of NHD in July and August for the 1980–2014 period.

Drought index		May			June			July		
		Corr	IP	BKS	Corr	IP	BKS	Corr	IP	BKS
NHD	$SPEI_3$	−0.60	−0.55	−0.51	−0.60	−0.59	−0.60	−0.79	−0.62	−0.79
	$SPEI_6$	−0.70	−0.49	−0.56	−0.66	−0.59	−0.59	−0.76	−0.68	−0.76
	$SPEI_9$	−0.66	−0.46	−0.52	−0.66	−0.52	−0.58	−0.77	−0.65	−0.77
	SPI_3	−0.65	−0.56	−0.57	−0.58	−0.57	−0.58	−0.74	−0.62	−0.73
	SPI_6	−0.69	−0.53	−0.60	−0.72	−0.60	−0.66	−0.76	−0.64	−0.76
	SPI_9	−0.63	−0.51	−0.55	−0.69	−0.51	−0.67	−0.81	−0.65	−0.78
NHN	$SPEI_3$	−0.63	−0.63	−0.30	−0.60	−0.55	−0.38	−0.65	−0.60	−0.59
	$SPEI_6$	−0.61	−0.61	−0.38	−0.66	−0.66	−0.38	−0.65	−0.64	−0.57
	$SPEI_9$	−0.57	−0.57	−0.38	−0.66	−0.66	−0.41	−0.64	−0.64	−0.56
	SPI_3	−0.63	−0.63	−0.30	−0.58	−0.58	−0.37	−0.57	−0.43	−0.57
	SPI_6	−0.62	−0.62	−0.44	−0.67	−0.67	−0.42	−0.64	−0.58	−0.55
	SPI_9	−0.57	−0.57	−0.39	−0.66	−0.66	−0.46	−0.66	−0.63	−0.57

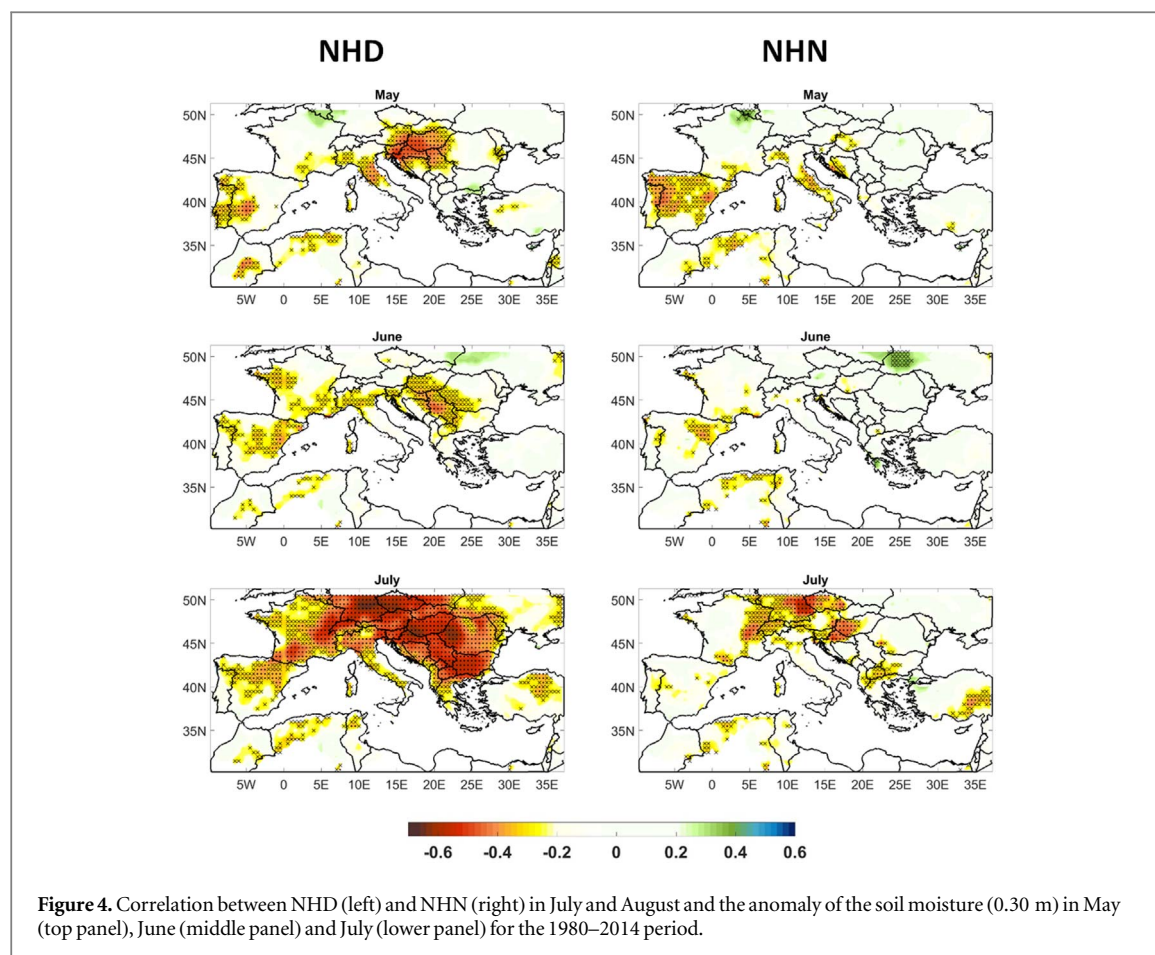
month lead as for the shorter timescales (3- or 6-month). This can be partially explained as the last 3 months are also included when longer timescales are calculated and these months can have a stronger influence than the previous months. Nevertheless, there are some exceptions. The most negative correlations identified in the IP are reached when SPI/SPEI at 3 months' time scale in May, or SPEI at 6 months' time scale in June, are correlated to the NHD/NHN, emphasizing the role of shortest time scales. However, when concurrent SPI/SPEI in July is correlated to the NHD/NHN in July and August, the most negative correlations identified in the IP are reached for the longest time scale (9 months), reflecting that the winter and spring water balance (precipitation-evaporation) have a major importance on the occurrence of NHD and NHN in the summer. In the case of the BKS, the most negative correlations identified in May or in June are mostly reached when SPI/SPEI at 6- and 9-months' time scales are correlated to the NHD/NHN. On the month of July, a dichotomic behavior appears when using SPI or SPEI. SPEI is better correlated for the 3 months' time scale and SPI for the 9 months, possibly reflecting the capacity of SPEI capturing earlier the balance between precipitation and evapotranspiration.

Precursor drought conditions relate more strongly to daytime hot extremes than nighttime temperatures. The correlations between the NHN in July and August and the preceding 3-, 6- and 9-month SPEI in the months of May to July (figures 1–3, right panel) also present significant spatial differences, as occurred for the NHD (figures 1–3, left panel). Nevertheless, the correlation values are usually lower than those reached by the NHD and with smaller spatial coverage. This might occur as the signal associated to the NHD (daytime maximum temperature) is tightly linked with SM via the control of SM on the partition between sensible and latent heat flux while minimum temperature is driven by the development of the nocturnal boundary

layer (Miralles *et al* 2014). Moreover, the high correlation values between NHN and the different time scales of SPEI, and SPI in May and June (figures 1–3), are mostly confined to the Iberian Peninsula and northern Africa, but virtually absent of most other areas in the Mediterranean.

In order to support these results, a correlation between the ERA-Interim/Land SM and the NHN and NHD was calculated for each month of the period 1980–2014.

Figure 4 shows the correlation strength for SM in the months of May to July and the NHN and NHD in July and August. The identified hot spots agree with the previous results for NHD/NHN in the Balkans and Iberia in May to July. The magnitude of the maximum (positive) correlation values obtained between the NHD/NHN with SM values in May, June and July are always considerably lower than the magnitude of the minimum (negative) correlation values (figure 4). The positive correlations are usually located in northern France, Germany, Albania, Romania, Bulgaria, Ukraine or Greece, and mostly not statistically significant. Conversely, negative significant correlations are more spatially generalized and are mostly located in the IP, southern France, northern Italy, the BKS and on northern Africa. The most negative correlations identified in the IP (central Iberia, −0.56) are reached when NHD is correlated with SM in May. In the case of BKS, the most negative correlations identified are reached when SM is correlated to the NHD in July (−0.77), with a high spatial coverage of most south-eastern Europe including the BKS. However, the correlation in May between SM and NHD is also high (−0.63) in BKS. The correlations between the NHN and SM have generally lower spatial coherence than the ones reached between NHD and SM. Moreover, the highest negative correlations are reached in May for the Iberia and July for Central Europe, whereas June only presents negative significant correlations in the northeastern area of the IP. The analysis of



consecutive months (figures 1–3) allows to identify that there is a spatial consistency on certain areas where consecutive months' present significant correlation values. This allows for the identification of hotspots of predictability of extreme hot temperatures and heatwaves in summer which are preceded by drought conditions in the spring or early summer (figure 5) which is of highly importance for seasonal forecasting (Ardilouze *et al* 2017). In the case of NHD, it is possible to identify four major hotspots, namely the IP, northern Italy, northern Africa and the BKS. In general, the hotspots are present for the 3 time scales but are more spatially coherent for the 6 months time scales. In the case of NHN, it is also possible to identify hotspots, although they are more spread and do not cover such large areas as by NHD. Nevertheless, certain areas of the IP and of the northern Africa show some spatial aggregation.

4. Discussion

The correlations between the NHD and NHN in July and August and the preceding 3-, 6- and 9-month SPI and SPEI in the months of May to July were evaluated and several regions exhibit significantly negative correlations, i.e. high NHD/NHN following negative SPI or SPEI values. This is in accordance with previous works which identify that low SM in the spring and

beginning of summer locally amplify hot extreme events in the Mediterranean and Europe. Namely, Fischer *et al* (2007) analyzed the soil-atmosphere feedbacks during four particularly important European heatwaves and concluded that land-atmosphere coupling plays an important role for the evolution of the investigated heatwaves both through local and remote effects, with largest impacts found for daily maximum temperatures during heatwave episodes. The analysis by Mueller and Seneviratne (2012) suggests a strong relationship between precipitation deficits and the subsequent occurrence of hot extremes in a large fraction of the world, Europe included. Similarly, Mazdiyasn and AghaKouchak (2015) and Sharma and Mujumdar (2017) respectively identified an increase in concurrent meteorological droughts and heatwaves in the United States and in India. In this study we go a step further, identifying regions with a consistent link between summer extreme temperatures and preceding (up to 2 months before) drought conditions.

The magnitude and spatial dispersion of correlation values obtained between the NHD or NHN with SPEI and SPI are generally similar and the most negative correlations identified differ in terms of time-scales for different areas. Particularly for the IP, the highest negative correlations are often observed for the smallest timescales (3- or 6-months), whereas, for

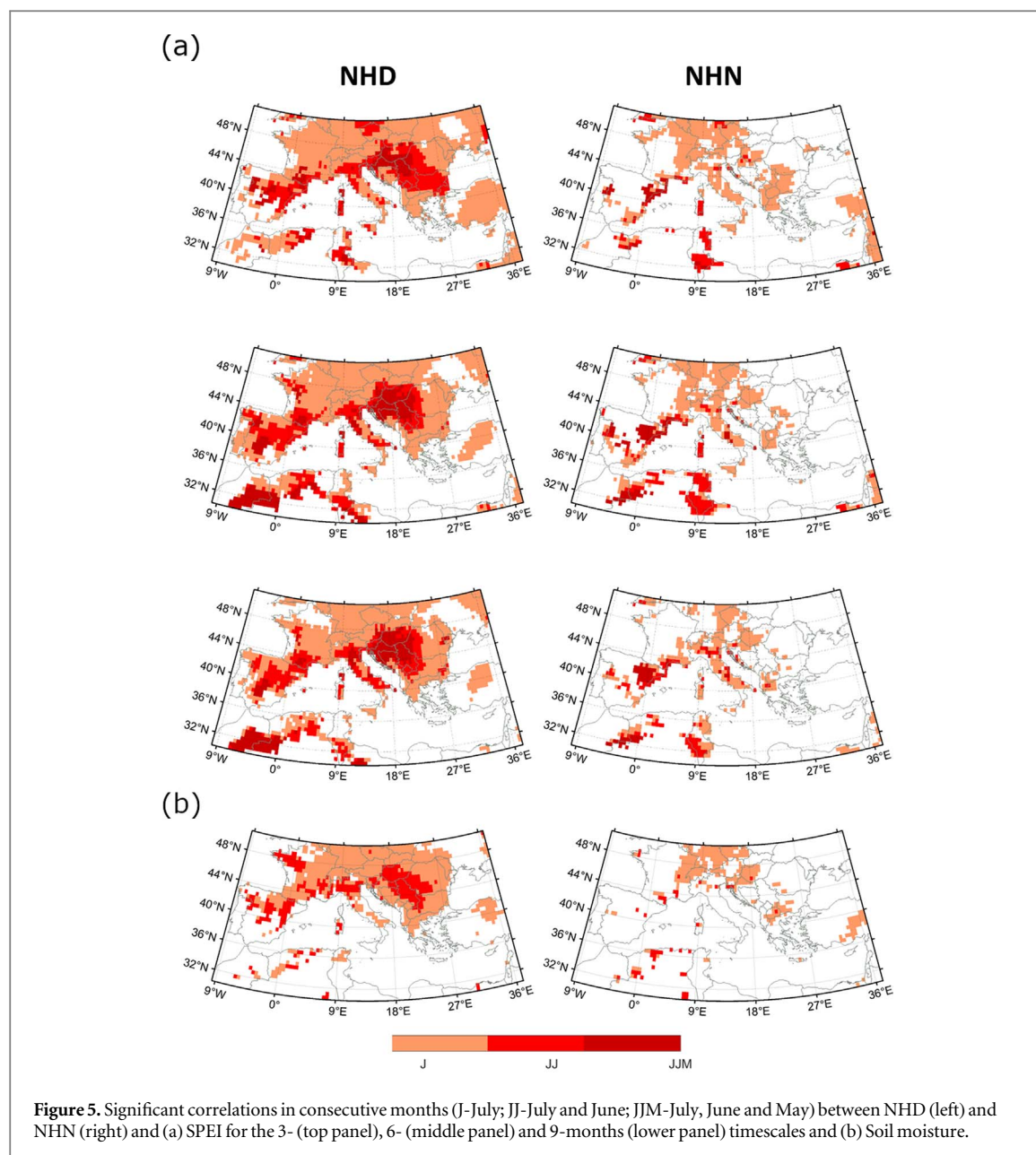


Figure 5. Significant correlations in consecutive months (J-July; JJ-July and June; JJM-July, June and May) between NHD (left) and NHN (right) and (a) SPEI for the 3- (top panel), 6- (middle panel) and 9-months (lower panel) timescales and (b) Soil moisture.

the case of BKS, they react differently for SPEI or SPI and for the different time-scales.

Over mid-latitudes the occurrence of extremely hot temperatures has been repeatedly reported to be associated to the establishment and persistency of certain atmospheric circulation patterns (e.g. Miralles *et al* 2014), particularly intense Ridges over the Mediterranean basin (Sánchez-Benítez *et al* 2017, Sousa *et al* 2017). Conversely, several other studies also pointed that the occurrence of such extreme events had also the contribution of pre-existing large negative SM anomalies (García-Herrera *et al* 2010, Miralles *et al* 2014, Zscheischler and Seneviratne 2017). The lack of precipitation and the associated depletion of SM results in reduced latent cooling and thereby amplify the summer temperature extremes (Fischer *et al* 2007). Another aspect which should be accounted is the contribution of the evapotranspiration during spring

and early summer which might be an important factor as local recycling may overlap the areas where the highest amount of rainfall is registered. This phenomenon has been identified to occur in the IP, where the recycling maxima overlaps with the areas where the highest amount of rainfall is registered (Rios-Entenza *et al* 2014). This connection, reaching its peak of intensity in April and May, confirms that the recycling contribution is critical to describe the occurrence (or not) of a spring peak of precipitation (and consequent SM contents) observed throughout most of the continental Iberia.

Apart from the more commonly analyzed daytime influence of high temperatures, nighttime extremes have also been referred as causing an additional burden to health (Murage *et al* 2017) and the environment (Miralles *et al* 2014, Gouveia *et al* 2016). Here, and despite the stronger relationship found between

drought conditions and daytime extreme events, the nighttime influence is not negligible. This was also identified by Miralles *et al* (2014) which examined the influence of daytime and nighttime contribution during pre-heatwave and mega-heatwave. They concluded that daytime and nighttime have a different contribution to the enhancement of major heatwaves, such as in Western Europe in 2003 and over Russia in 2010. During daytime, heat is supplied by large-scale horizontal advection, warming of an increasingly desiccated land surface and enhanced entrainment of warm air into the atmospheric boundary layer. In contrast, during the night, the heat generated during the day is kept in a growing mixed boundary layer, resulting in a progressive accumulation of heat over several days, which enhances soil desiccation and leads to further escalation in air temperatures (Miralles *et al* 2014). Deep and warm nocturnal residual layers formed and detached from the surface by a strong ground thermal inversion. Such residual layers have the potential to intensify diurnal temperatures by storing heat from one day to the next, as the warm air from the residual layer continually feedback itself again into the diurnal atmospheric boundary layer (Miralles *et al* 2014).

The present approach makes a comparison between the use of two well-known drought indicators, SPI and SPEI, both presenting some advantages and drawbacks which were previously mentioned. In order to support the results reached when using SPI and SPEI as proxy for SM, the ERA-Interim/Land SM dataset was correlated with the NHN and NHD month by month. Although the SM product is a models output, the use of this dataset provides an integrated and physically coherent estimate of SM and snow water equivalent (Balsamo *et al* 2015), which can allow for more complementary information on SM than the solely use of SM proxies or SM measurements resulting from sparse monitoring stations. Despite the very different nature of this SM database, it is worth noting that the identified hot spots between the NHN and NHD and the ERA-Interim/Land SM dataset agree well with the previous results for NHD/NHN in the Balkans and Iberia in May, June and July. The NHD results are also in accordance with model-based studies investigating the role of SM initial conditions on temperature predictability (Prodhomme *et al* 2016, Ardilouze *et al* 2017) which identifies the Balkans hotspot for forecasts initialized in May and valid for June–July. However, those studies did not find any clear signal over Iberia, as our results suggest. This could be due to several reasons, but considering the observational evidence, the lack of signal in the seasonal forecast models in Iberia is worth to be further investigated.

One of the most important outcomes of this study is the proven ability to identify hotspots of predictability of extreme temperatures in summer in the IP,

northern Italy, northern Africa and the BKS linked to the occurrence of drought events in the spring or early summer (figure 5). These results are of high importance for climate modelers (Ardilouze *et al* 2017) and responsible authorities, as the occurrence of drought induced extreme temperatures, in particular heatwaves, can have costly impacts (Díaz *et al* 2006 Sánchez-Benítez *et al* 2017). The hotspots in the BKS and northern Italy were previously identified and analyzed for SM-temperature feedbacks (Whan *et al* 2015, Ardilouze *et al* 2017).

This study might be a starting point to assess the possibility of certain future circumstances in SM having high probability of contributing to the occurrence of summer NHD/NHN. Nevertheless, some other aspects like the land use and land use change should be taken into account when studying past and future changes in heat extremes, and highlight a potentially overlooked co-benefit of forest-based carbon mitigation through local bio-geophysical mechanisms (Lejeune *et al* 2018). Finally, the increasing resolutions of regional climate simulations fosters our ability to understand how, in the context of climate change, the land-atmosphere coupling will evolve and contribute to expected growth of the occurrence of extreme temperatures in the Mediterranean.

5. Conclusions

The main objective of this work was to assess to what extent the occurrence of extremely hot months in the Mediterranean region are preceded by the occurrence of drought events in spring and early summer. Most Mediterranean regions exhibit significantly negative correlations, i.e. high NHD/NHN following negative SPEI/SPI values, and thus a potential for early warning. On the other hand, the correlation values for NHN are usually lower than those reached by the NHD and with smaller spatial dispersion. It is also important to stress that the use of the ERA-Interim/Land SM dataset supports the results reached previously.

Intrinsically, the findings suggest some predictive capacity of drought indicators and SM data through the identification of hotspots to anticipate a higher probability of occurrence of extreme events in the summer heat. The knowledge that surface moisture deficits are a relevant factor for the occurrence of hot extremes suggests that hot day predictions could be substantially improved in operational forecasts in those regions. Although a predictive approach is out of scope of this study, our results provide a new observational insight on the links between preceding drought conditions and temperature anomalies that can be further investigated in coupled seasonal forecast systems.

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